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TURBULENT STRUCTURE OF STABLY STRATIFIED NOCTURNAL
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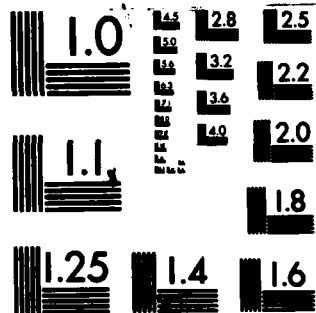
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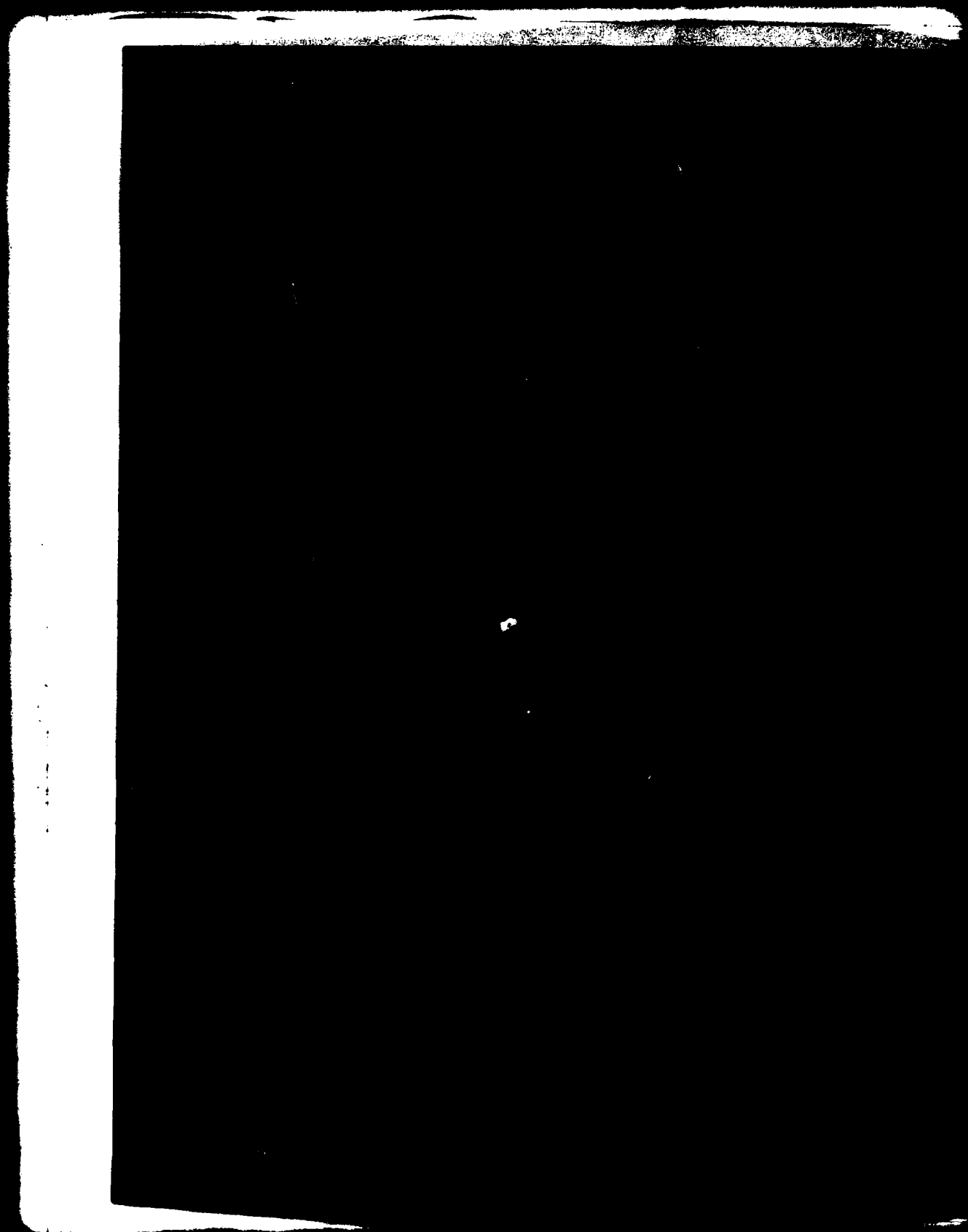
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<p>→ A series of measurements of the mean and turbulent structure of winds and temperatures over a simple slope during stable nocturnal flows has been carried out. Data from propeller and sonic anemometers, aspirated thermistors, and fast-response platinum resistance thermometers were recorded and analyzed. For moderate downslope flows driven by ambient winds or for winds predominantly in the cross-slope direction, the wind and temperature structure generally resembled that found over flat terrain. During drainage</p>		

20. flows, however, the jet in the downslope wind component caused significant changes in the turbulence profiles. Turbulent kinetic energy can increase with height, and the turbulent transport of momentum can reverse sign and be directed upward. Several implications of the drainage wind structure are discussed, and future studies are outlined.

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INTRODUCTION

Under stable nocturnal conditions, the transport and diffusion of atmospheric pollutants may be markedly different from that encountered during unstable periods. Numerous studies of the stable boundary layer characteristics have been conducted, and increasing interest in the influence of topography on these characteristics is apparent [e.g., Gudiksen and Dickerson (1)]. Modeling studies [e.g., Brost and Wyngaard (2)] have shown that even slight terrain slopes can have noticeable effects on the behavior of stable boundary layers; in the presence of significant slopes the results may be even more dramatic. However, there has been relatively little investigation of the turbulent structure of stable nocturnal layers over complex terrain. Since the turbulent structure has a profound effect on the dynamics of the layer as well as the dispersion of pollutants in the layer, it is clearly important to obtain a greater understanding of such influences. Unfortunately, the topographical effects on both the mean and turbulent wind and temperature structures can be extremely complex, and one must employ some appropriate strategy in these investigations if a never-ending series of "case studies" is to be avoided. One approach, represented by the work to be described here, is to start with a simple terrain feature and study its effects in some detail; a succession of topographically more complex forms may then be investigated to compare and contrast their effects.

In the presence of strong radiational cooling of the surface, the winds over a simple slope are expected to develop a near-surface maximum in the downslope component. Previous observational and modeling studies (3-6) showed that the strength and height of this jet are functions of the ambient temperature and wind fields as well as the topography. The mean and turbulent structure of winds and temperatures in such flows can differ substantially from that found in stable nocturnal flows over flat terrain. The objective of this project has been to characterize this structure and these differences.

In this interim report, we describe a series of wind and temperature measurements carried out over a simple slope. The nature of the site, the deployment of the instruments, and the procedures for the collection and reduction of the data are given. Comparisons with results normally found over flat terrain are also made, and a number of practical implications are discussed. In the final report for this project, a more detailed analysis of the data will be presented, and some of the topics to be included are listed in the Results and Discussion section.

MEASUREMENTS

The site chosen for the measurements was a ridge on the southeastern portion of Rattlesnake Mountain, near Richland, Washington. The northeastern slope of the ridge forms a nearly two-dimensional tilted plain with a vertical drop of ~ 170 m from the ridge line to a point where the slope changes rather abruptly from 21° to 8° . The vegetation on the slope is sparse, and canopy effects are expected to be minimal.

The length of the two-dimensional portion of the ridge is about 2 km. An 18-m tower was located in the approximate center of this section, about 150 m below the ridge line. Three-component Gill® propeller anemometers were mounted on this tower at heights of 0.97, 2.3, 3.6, 5.3, 8.4, 12.9, and 17.9 m. Aspirated thermistors were also placed on the tower at heights of 0.47, 1.2, 2.4, 3.9, 5.4, 8.5, 13.0, and 18.0 m.

A second, shorter tower was located about 10 m cross-slope from the first tower. Two sonic anemometers and two fast-response platinum resistance thermometers were mounted on this tower. The height of the upper instruments was ~ 3.2 m; for the lower instruments, the u and v components of the sonic were just below 1.9 m while the w sensor and the temperature sensor were slightly below 1.5 m. This separation of components was caused by the necessity of mounting one of the sonics such that it faced directly uphill. Since the w and T probes extended beyond the u and v probes, they were located farther up the slope and, thus, closer to the surface.

Additional information was obtained from a third tower located ~ 70 m below the ridge line. This 12-m tower was equipped with 6 levels of instrumentation to provide mean profiles of wind speed, direction, and temperature. A tethered sonde was also flown during several of the nights when measurements were taken to provide information on mean wind and temperature fields aloft. These supplementary data were obtained through a cooperative research program funded by the Department of Energy under contract DE-AC06-76RLO 1830.

The sonic and fast temperature data were sampled at intervals of 60 ms during initial measurements; for the later runs an interval of 70 ms was used after it was noted that intermittent data scans were being missed by the data acquisition system. The instruments on the main tower were sampled at a rate 20 times slower than the sonics (i.e., at 1.2- or 1.4-s intervals), and the instruments on the upper tower were sampled at a rate 3 times slower than that. All data were stored on magnetic tape and subsequently processed on a computer.

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DATA SELECTION AND PROCESSING

The occurrence of slope winds on Rattlesnake Mountain is a rather intermittent phenomenon. The exposed nature of the slope and the small vertical drop from the ridge to the observation site imply that the weak drainage flows can easily be obscured by larger scale wind patterns unrelated to the local surface cooling. We collected over 34 hours of data on 6 different nights, but actual drainage winds occurred during only a fraction of this time. Thus, the selection of suitable nights for measurements was often problematical, and we were fortunate to obtain several nights' observations useful for our study.

The selection of particular periods for analysis was based on two factors. Since the quantity of data to be processed in any period is large and the turbulence analysis is labor intensive, the mean wind characteristics during any period should be "representative", i.e., they should be characteristic of a class of conditions that we wish to study. In addition, the data collected during the period should be of good quality.

This second criterion was more difficult to meet than had been anticipated. The sonic anemometers proved somewhat temperamental to operate, particularly a new one purchased for this project. As the measurements progressed, we were able to overcome many of the electronic noise problems encountered, but the lack of a longer lead time between receipt of the anemometer and its use in the field was troublesome.

Two principal difficulties in the use of sonic data were found. The first was the presence of spiking (i.e., large jumps in the output voltage of the sonics that do not reflect changes in wind speed). During many periods, the spiking in one or more sonic components was sufficiently prevalent that the data were judged not to be useful for further analysis. In cases where minimal spiking was encountered, we employed a digital filter to smooth out the data. When a spike was encountered in a wind component's time series, a linear interpolation was made from the last valid datum until the voltage spike returned to within 1.5 standard deviations of the running mean of the series. The running mean was calculated with a recursive filter with an effective time constant of $142 \Delta t$, where Δt is the time interval between successive points. In the first of the observed cases discussed in this report, about 9% of the values from one sonic axis were affected by this filter; in all other cases, the effect was an order of magnitude or more smaller, and in many cases no data had to be filtered.

The second difficulty was the determination of the proper zero offset to use in processing the sonic data. The sonic anemometer measures speeds by timing the arrival of two sound pulses emitted in opposite directions from transducers. The difference in transit times depends on the wind speed along the axis of propagation of the pulses. Ideally, in a zero wind environment, the time difference should be zero. In practice, slight differences in path lengths for the two pulses or in the setting of various levels in the electronic circuitry can result in a voltage output in the absence of any wind. The normal procedure is to enclose the probes with a flexible tube that shields the transducers from ambient winds and then take a reading of the output voltage. It was found, however, that the voltage obtained in this manner was not necessarily the same as that obtained when the instrument was sitting in still air in a wind tunnel. The manufacturer said such a result is not surprising in view of the possibility of reflections off the enclosing tube. Moreover, a wind tunnel calibration extrapolated to zero wind speed gave yet another voltage value for the offset. The differences are on the order of only 10 mV or less ($1.0 \text{ V} \sim 9.8 \text{ m/s}$), but in the light winds encountered for many of our measurements, the uncertainty introduced by the offsets is larger than desirable. Thus, in presentations of observed mean wind profiles, we have occasionally smoothed some of the curves slightly to remove small kinks introduced when the Gills® and sonics are compared on the same plot.

In analyzing the wind structure over simple slopes, there are a variety of coordinate systems that suggest themselves. We chose to rotate the winds into a system in which the "horizontal" components are parallel to the local surface and the "vertical" winds are normal to the surface. This implicitly assumes that the mean streamlines are parallel to the slope. The data suggest that this is a reasonable approximation close to the surface but not necessarily as good at greater elevations. Since most of our interest will be in the first few meters above the slope, the choice seems appropriate. For spectral analyses, the winds were also rotated about an axis normal to the surface into a system in which the u component is parallel to the mean flow and $\bar{v} = 0$.

RESULTS AND DISCUSSION

At this point it is useful to review the expected profiles of wind and temperature in stable conditions over flat terrain, and to consider the resultant turbulence behavior. Figure 1 shows mean wind and temperature as a function of height over level ground, assuming a value for the friction velocity u_* of 0.15 m/s, and a Monin-Obukhov length L of 10 m. The profiles are based on observations by many observers; for a useful review of the relevant formulas, see Hanna et al. (7). For simplicity we have assumed that the surface flux layer extends to ~ 20 m. For a value of $L = 10$ m this is unlikely, and the actual wind speed is more likely to have a slower increase with elevation than the log-linear behavior shown here.

Turbulent kinetic energy is generated mechanically at a rate proportional to the shear in the mean wind speed, and buoyant suppression and dissipation balance the production. The resultant spectra of turbulent fluctuations in the mean velocity component u are shown in Figure 2 (8). The spectral amplitudes decrease with height, and there is a shift in the peak of the spectrum toward lower frequencies. If the wind increases with height more slowly than shown in Figure 1, as suggested above, the decrease in turbulent energy becomes more pronounced. In general, the total turbulent kinetic energy decreases linearly with height until the surface-induced mechanical turbulence vanishes at some elevation z_i ; above z_i the turbulence is intermittent and weak.

For this interim report we present results from 3 cases. During the first of these, the winds were essentially downslope and of modest strength, the surface temperature inversion was weak, and there was little if any evidence of a drainage wind. The other 2 cases, taken on a different night, show a transition from a good drainage wind case with little or no cross-slope component to a situation in which the winds near the surface are almost completely cross-slope and only a small drainage component remains. This combination of examples illustrates many of the principal differences between flows over level ground and simple slopes.

Figure 3 shows observed wind and temperature profiles on Rattlesnake Mountain during the early morning hours of September 4, 1983 (Run 2). During this period of moderately strong ambient winds, the flows were almost entirely in the downslope direction but evidently not driven by katabatic forces. Under such circumstances we anticipated that the turbulent features would not be very different from those encountered over level ground, since the general profiles of wind speed are similar. This is borne out in Figure 4, where u spectra from a Gill® anemometer and the two sonic anemometers are shown. The frequency response of the Gill® anemometer is significantly more limited than that of the sonics and is not reliable much above 0.1 Hz. We shall also restrict our present discussion to frequencies above about 0.01

Hz; below that value wave effects are suggested by some of the data and will be discussed in another report. The spectral amplitudes at the 3 levels are similar, with the 3.2-m sonic values falling a bit below the 1.9-m sonic values at the higher frequencies.

In contrast to this behavior, we present the case shown in Figure 5. These data were obtained during the night of September 11, 1984 and show a shallow, well-defined drainage flow with the maximum speed of the downslope component apparently lying below a height of about 1 m (Run 4A). The cross-slope component is very small over the full extent of the tower. The inversion is quite strong and shows a sharp break between 2 and 3 m. Figure 6 shows the wind spectra along the mean flow direction, and the difference from the previous case is evident. Here, the turbulent kinetic energy is larger at the higher elevations, as seen from the 1.9- and 3.2-m spectra. Perhaps more dramatic is the behavior of the cospectrum of u and w . This is shown in Figure 7, where the momentum transport at the levels of both sonics is seen to be directed upward, in contrast to the usual behavior over flat terrain or that found in the first case discussed (Run 2). This was expected, since the gradient of the mean wind was negative here. Although the Gill[®] anemometer at ~ 1 m did not have a sufficiently fast frequency response to give a reliable, quantitative value of $\overline{u'w'}$, its sign was positive, consistent with the upward momentum transport found at greater elevations.

As the night progressed, the winds increased in strength and shifted to a cross-slope direction, and the temperature inversion weakened (Run 4D). About 1 hour and 45 minutes after the period represented in Figure 5, the wind and temperature profiles were as shown in Figure 8. The downslope component of the wind has almost vanished, and only a weak drainage wind is present. The spectra cluster together (Figure 9) and the uw cospectra again show a net downward transport of momentum at both sonic levels, as seen in Figure 10. In all of the cases discussed here, the cospectra of wT' are negative, consistent with the stable stratification we observed.

It is apparent that the wind profiles and resultant turbulence over a simple slope where drainage winds are present can be substantially different from that found over flat terrain. The surface flux layer in slope winds may be extremely shallow, and reversal of the direction of momentum flux can occur very close to the surface. This presents an interesting problem in specifying boundary conditions for dynamic models, which frequently make use of some assumption about constant fluxes near the ground. The grid level at which this is permissible may be distressingly low for use in many numerical models. We anticipate that the surface friction velocity will not be a useful parameter for describing the flow fields over any significant depth. The shallow flow layers associated with drainage winds over simple slopes also present an interesting observational problem. Measurements of wind speeds and directions at some near-surface height (e.g., 2 m) may be very poor indicators of the wind field at somewhat higher elevations.

A number of models (3,4,6,9,10) relate the local exchange parameters of the atmosphere, for heat, momentum, and passive contaminants, to the local turbulent kinetic energy. Over flat terrain, the energy decreases monotonically with height. The spectra previously shown suggest that this is not the case in drainage winds. It is difficult to quantify this behavior since the frequency response of the Gill® anemometers is inadequate to capture the full extent of the important fluctuations in the winds. However, we may obtain some indication of trends by examining the total variance in the winds, $u'^2 + v'^2 + w'^2$, between two fixed frequency limits. We chose 0.01 to 0.1 Hz. Below this band, the variance is likely to be affected by waves; above this band, the low wind speeds and slow response of the Gills® makes quantitative estimates unreliable. Within this band we can use results from both the sonic and the Gill® anemometers and, thus, obtain good resolution in the vertical profiles. It is interesting to note that the frequency response of propeller anemometers generally improves with increasing measurement height. However, in drainage winds the response may be worse at higher elevations, since the wind speed can decrease with height.

In Figure 11 we have plotted the ratio of the variance at a given height to that at 1 m elevation. Three of the curves give ratios of unity to within about 20%. These three correspond to the hypothetical flat terrain case and Runs 2 and 4D, where the drainage flows were weak or absent. The notable exception is Run 4A, where the variance increases with height. Similar behavior was found for other periods of drainage winds not discussed in this report. We carried out another calculation using only the data from the sonic anemometers, but encompassing a frequency band of 0.01 to 1 Hz. The results were similar; the ratios of the variances at 3.2 and 1.9 m were 0.79, 1.43 and 1.03 for Runs 2, 4A, and 4D, respectively. This behavior raises the possibility of enhanced diffusion in the levels immediately above the height of the downslope wind maximum, even in the presence of a strong surface inversion. The implications of this turbulent kinetic energy structure have not been considered in detail, but it seems likely that current diffusion theory, normally applied over flat terrain, may be inadequate over simple slopes.

In a future analysis we hope to consider a number of topics suggested by these data. These include an examination of the development and destruction of the drainage flows, a study of the contributions of wave motion to the spectral behavior, and an effort to obtain dimensionless wind and temperature gradients and compare their properties with those found over level ground. Further implications for modelling studies and the diffusion of atmospheric pollutants will be discussed. We will also attempt to broaden the data base with which to do these studies by searching for additional periods when at least one of the sonic anemometers was not "noisy" and, possibly, by using data collected in Colorado in the fall of 1984 as part of the ASCOT program.

FLAT TERRAIN

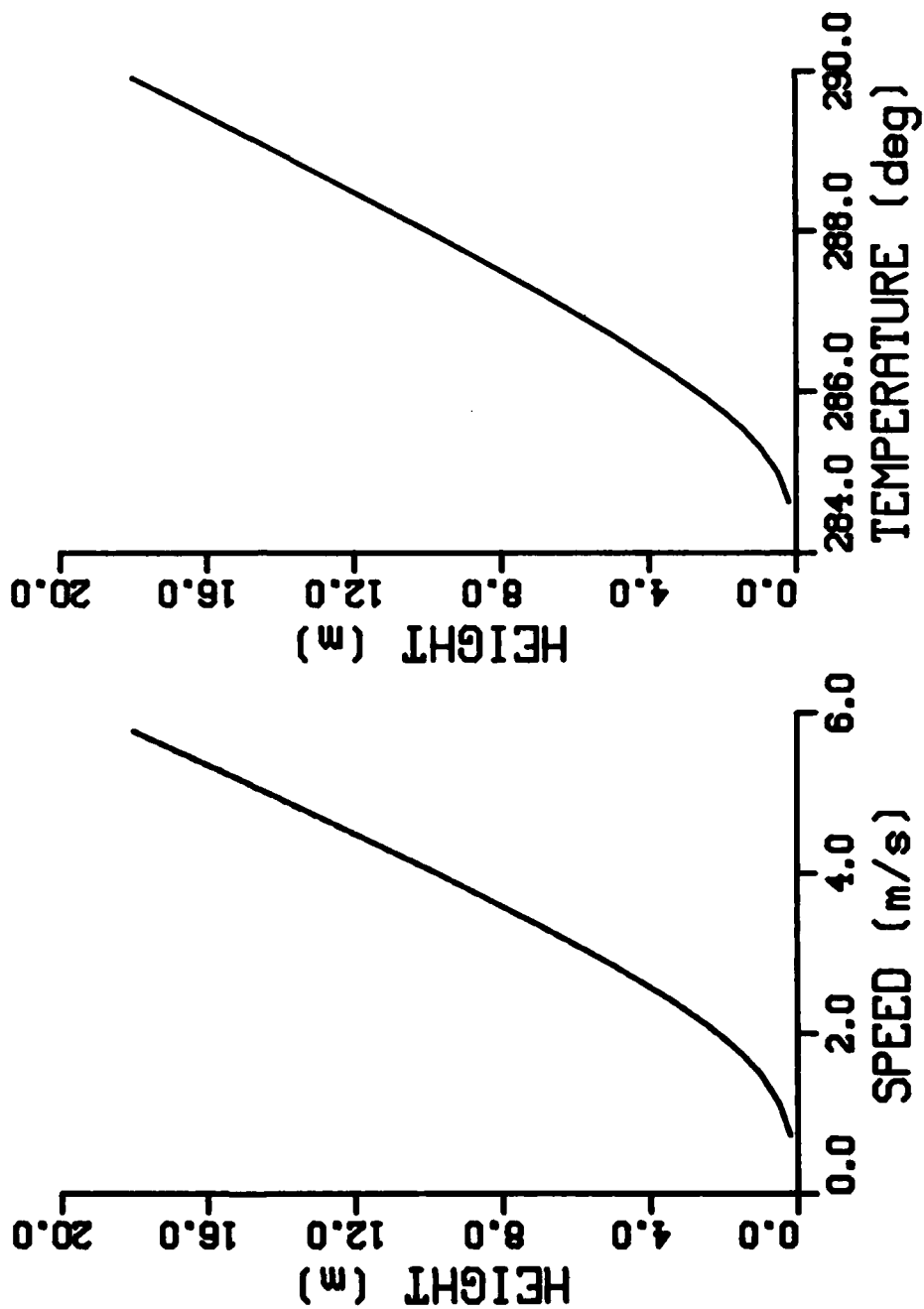


FIGURE 1. Hypothetical Wind Speed and Temperature Profiles over Flat Terrain

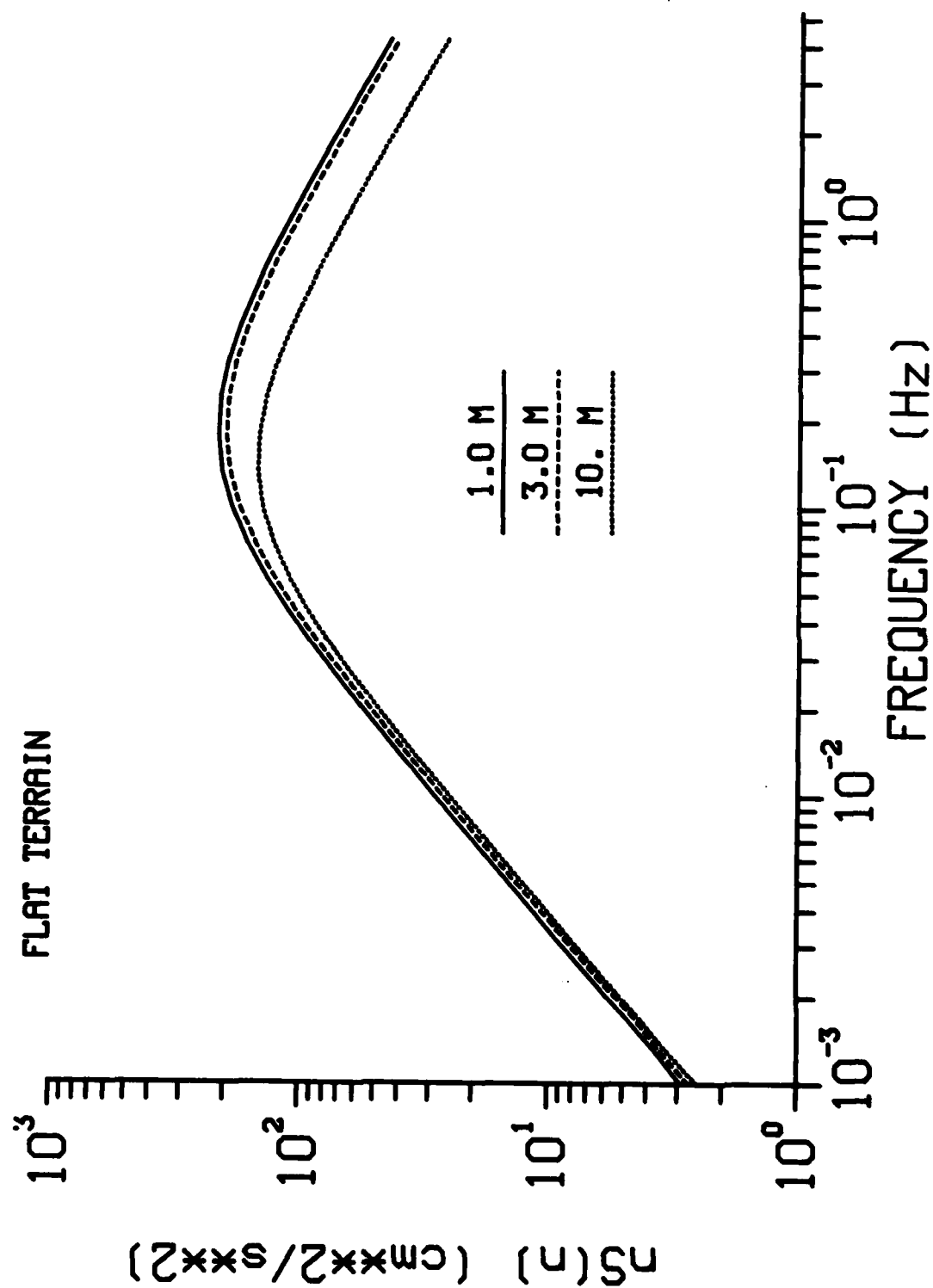


FIGURE 2. Hypothetical Spectra of u Component of Wind over Flat Terrain

RUN 2

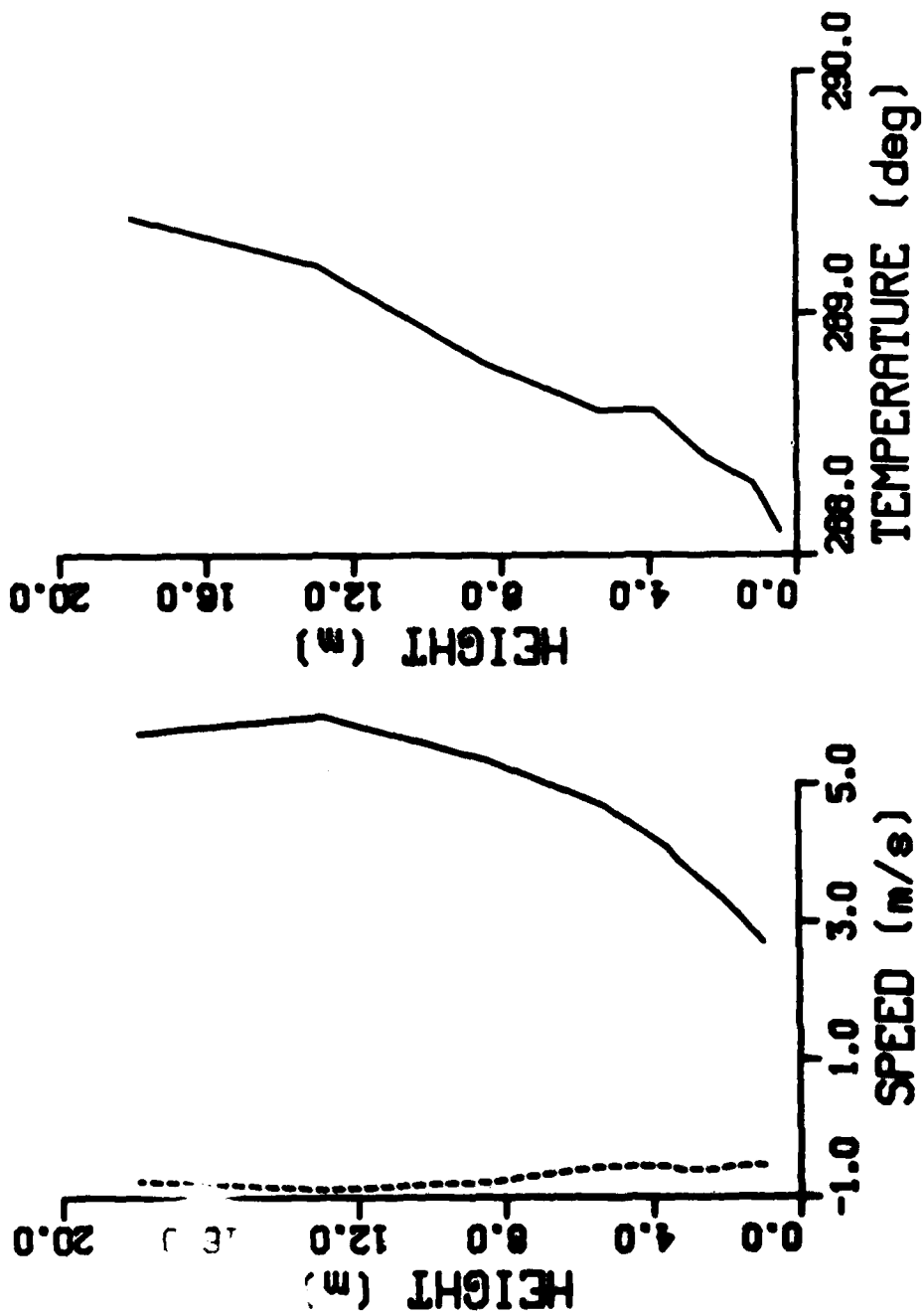


FIGURE 3. Profiles of u (Solid Line), v (Dashed Line) and Temperature on Rattlesnake Mountain, Run 2

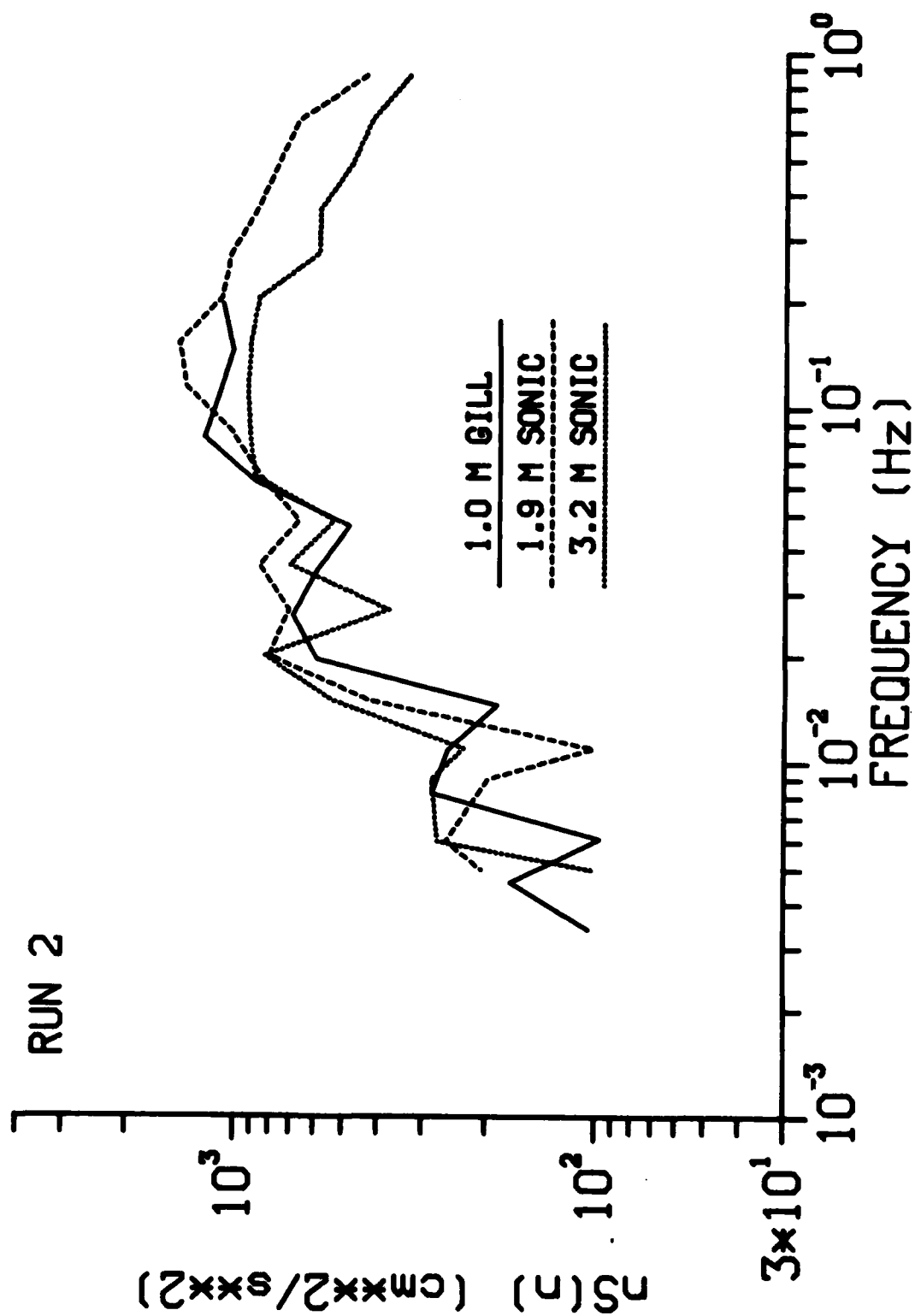


FIGURE 4. Spectra of u Component of Wind on Rattlesnake Mountain, Run 2

RUN 4A

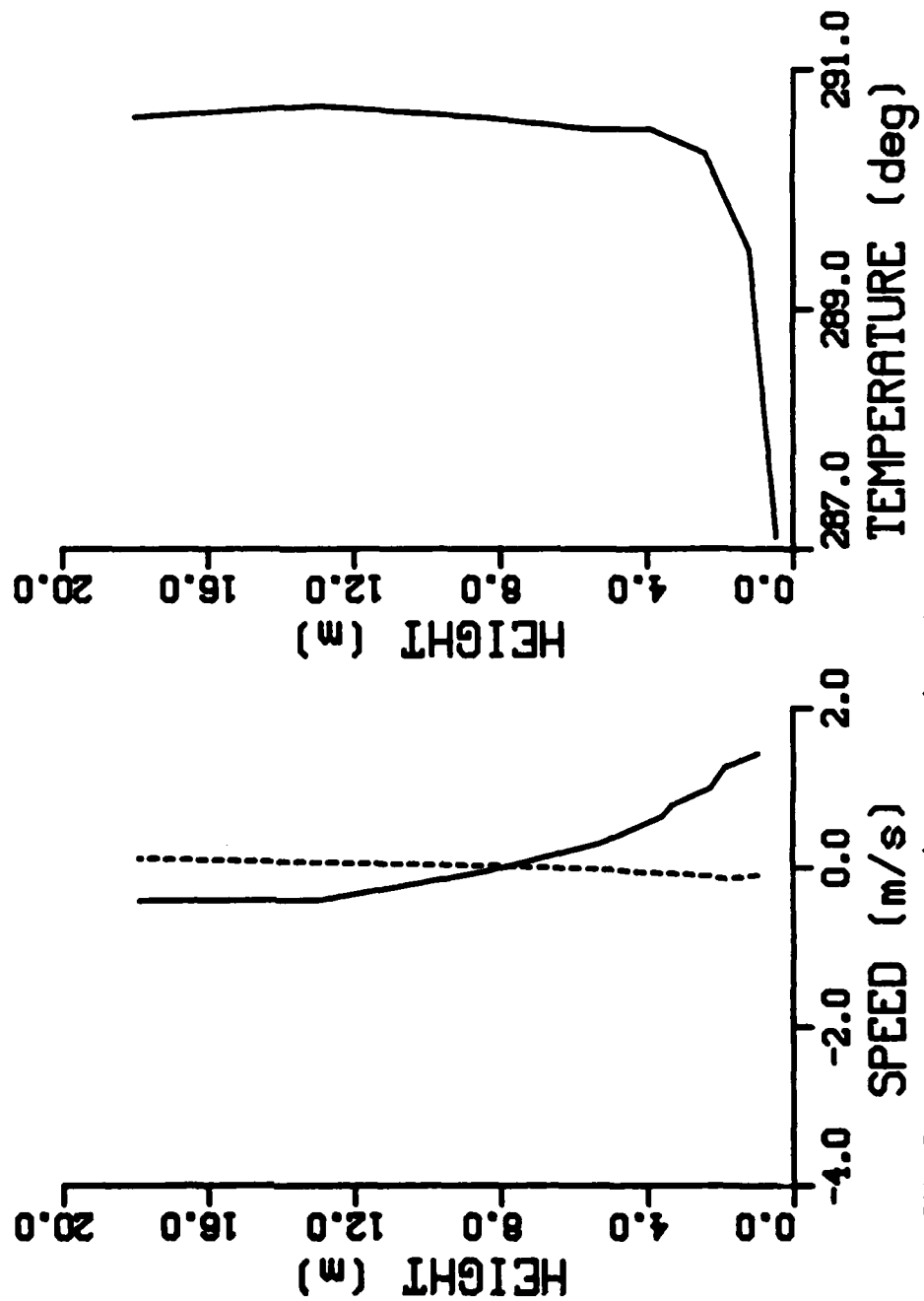


FIGURE 5. Profiles of u (Solid Line), v (Dashed Line) and Temperature on Rattlesnake Mountain, Run 4A

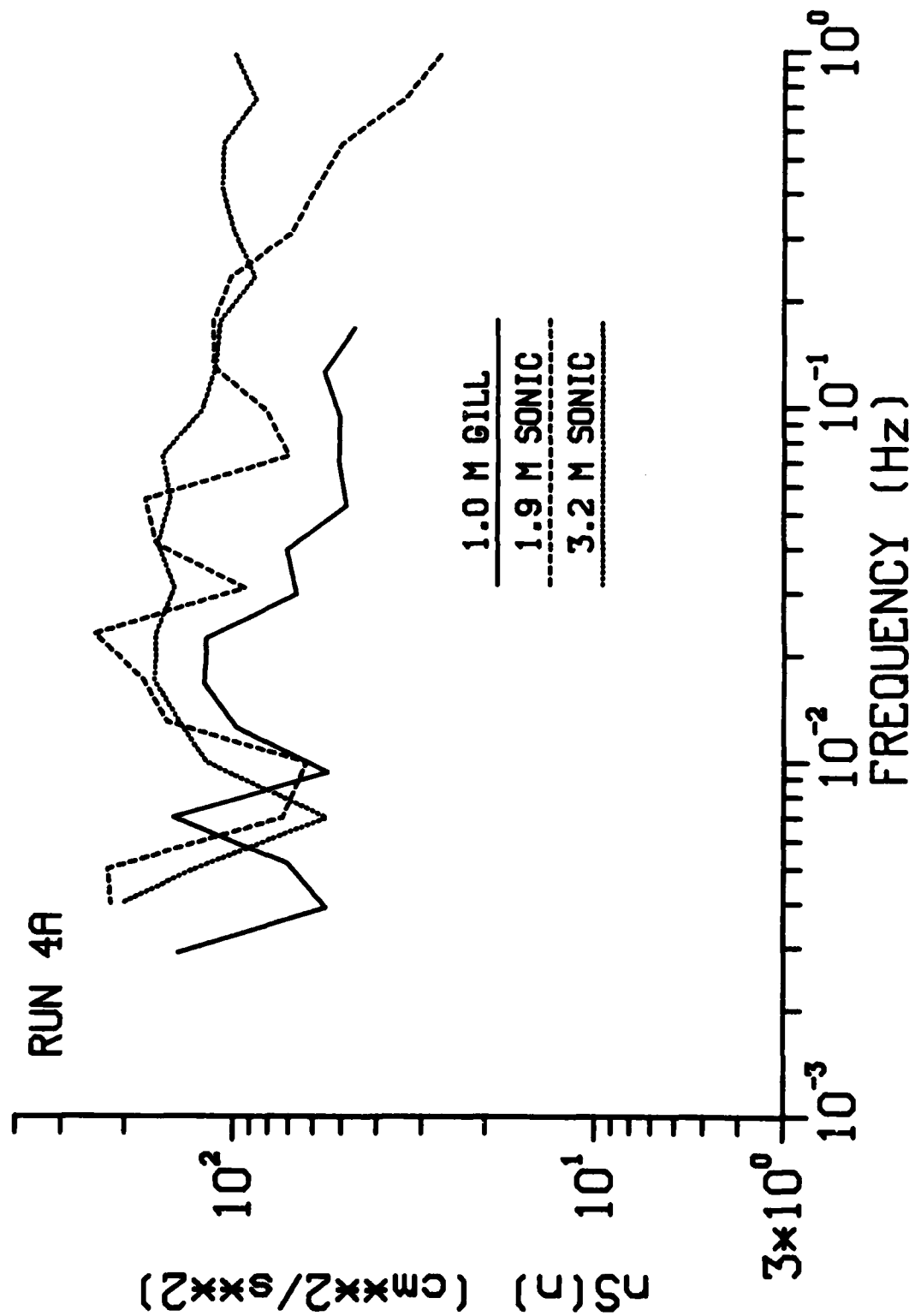


FIGURE 6. Spectra of u Component of Wind on Rattlesnake Mountain, Run 4A

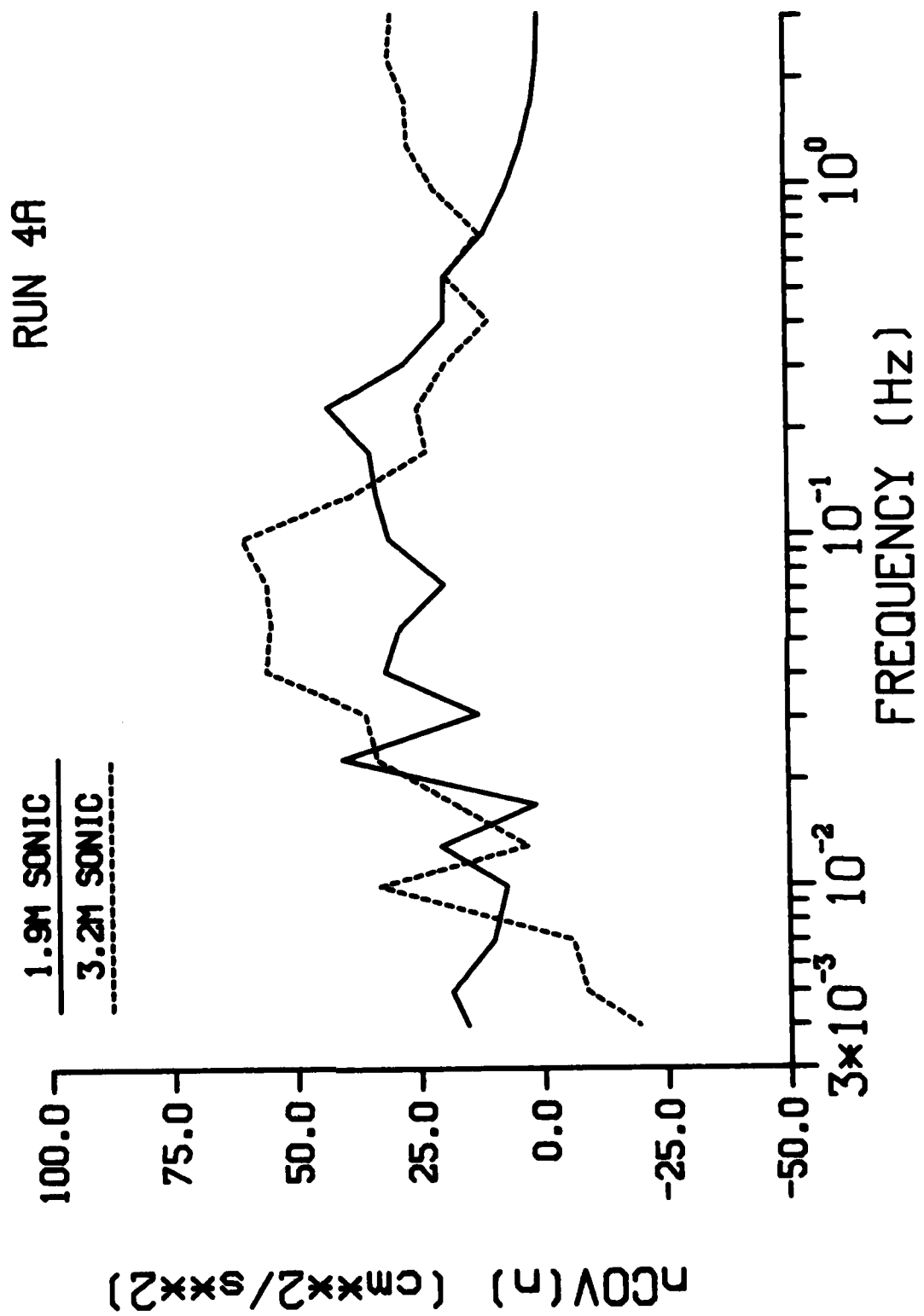


FIGURE 7. Cospectra of u and w on Rattlesnake Mountain, Run 4A

RUN 4D

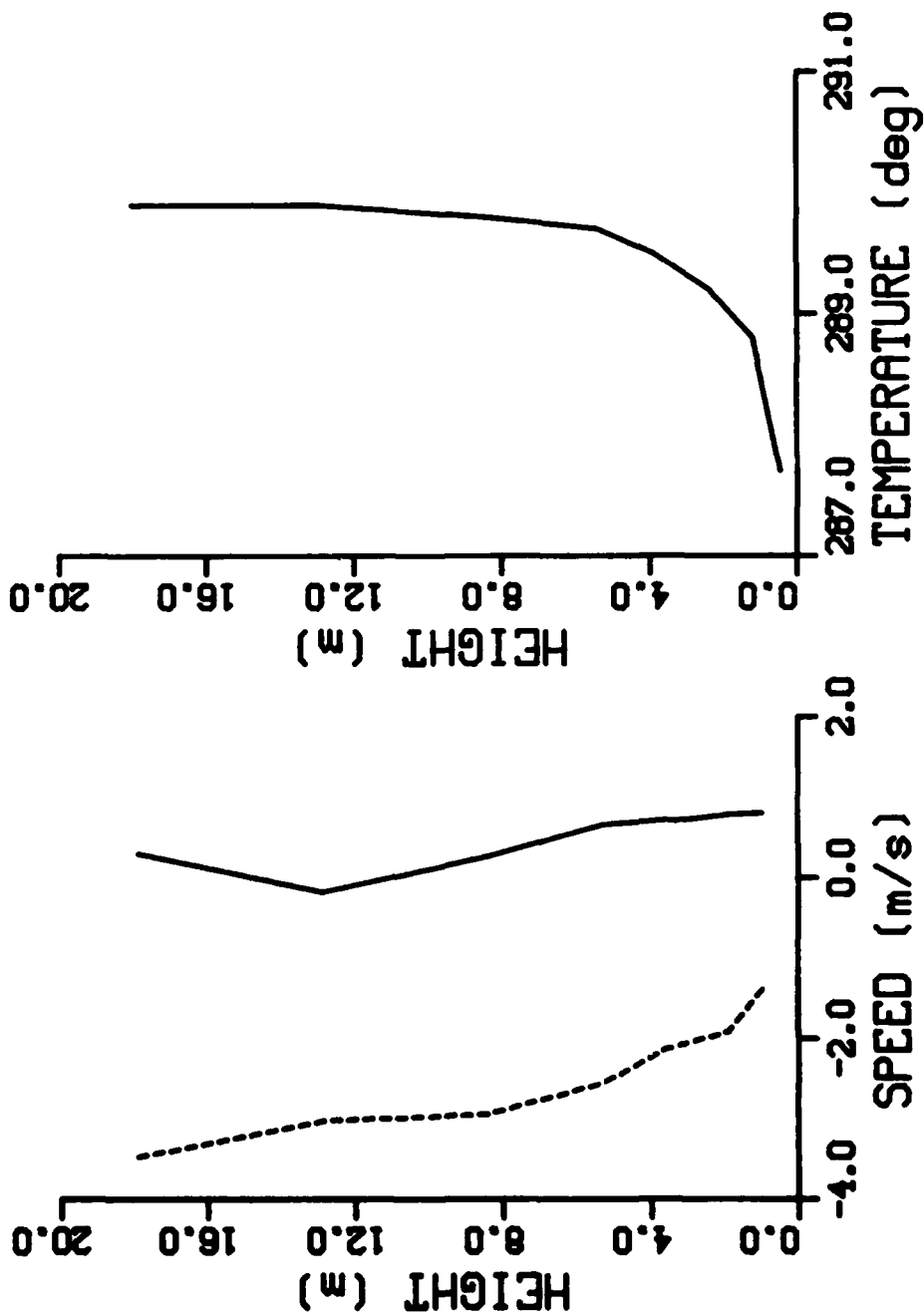


FIGURE 8. Profiles of u (Solid Line), v (Dashed Line) and Temperature on Rattlesnake Mountain, Run 4D

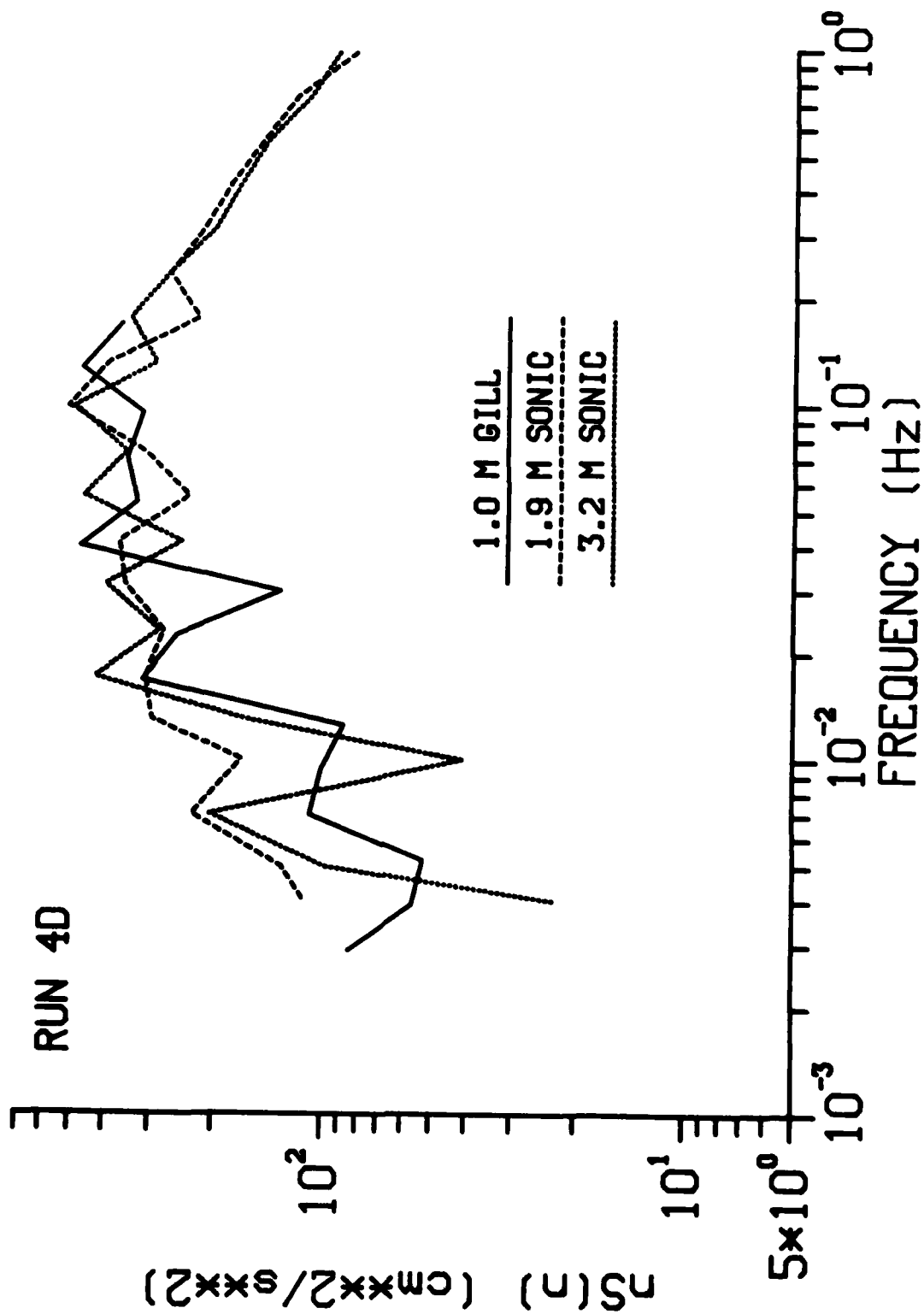


FIGURE 9. Spectra of u Component of Wind on Rattlesnake Mountain, Run 4D

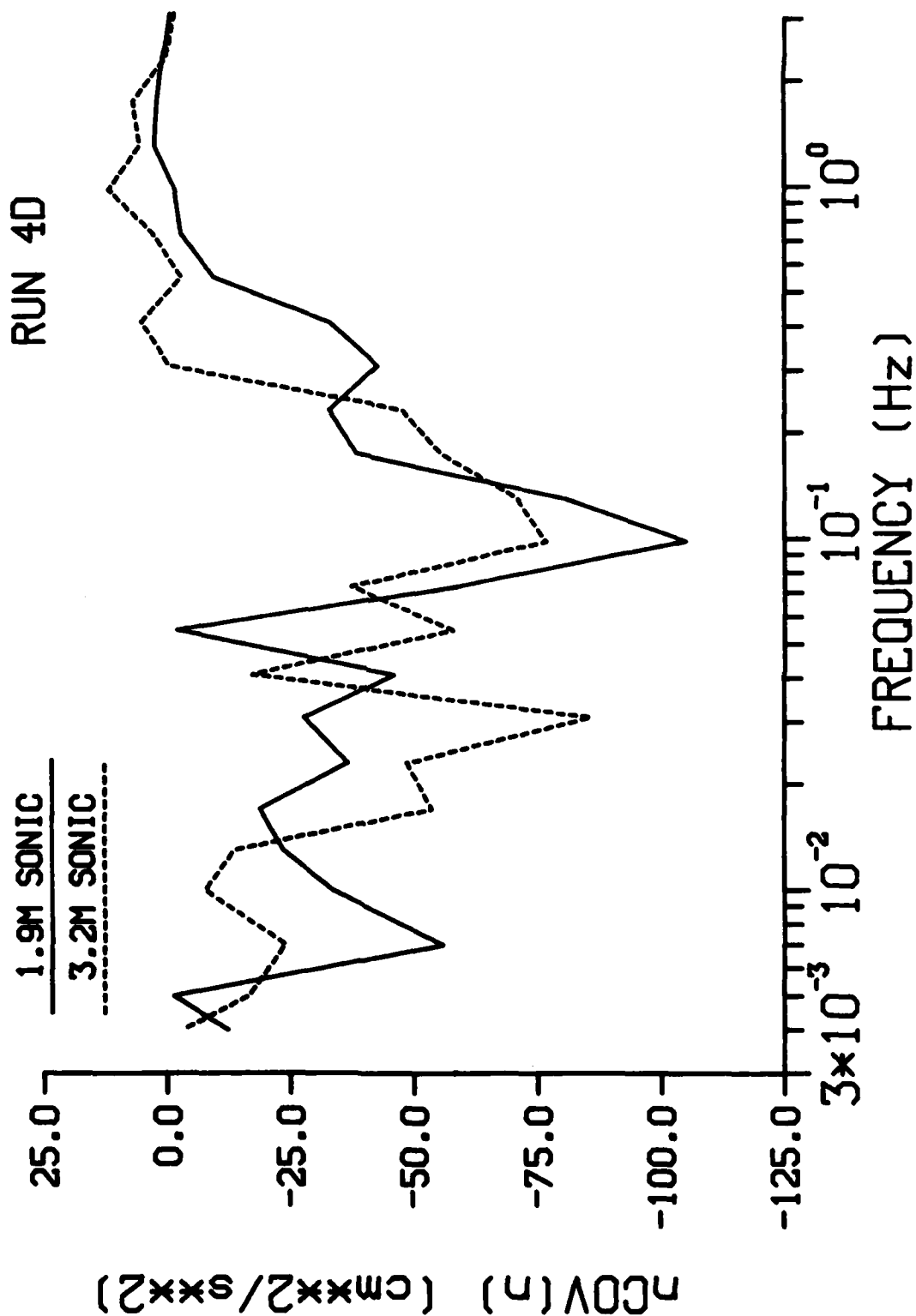


FIGURE 10. Cospectra of u and w on Rattlesnake Mountain, Run 4D

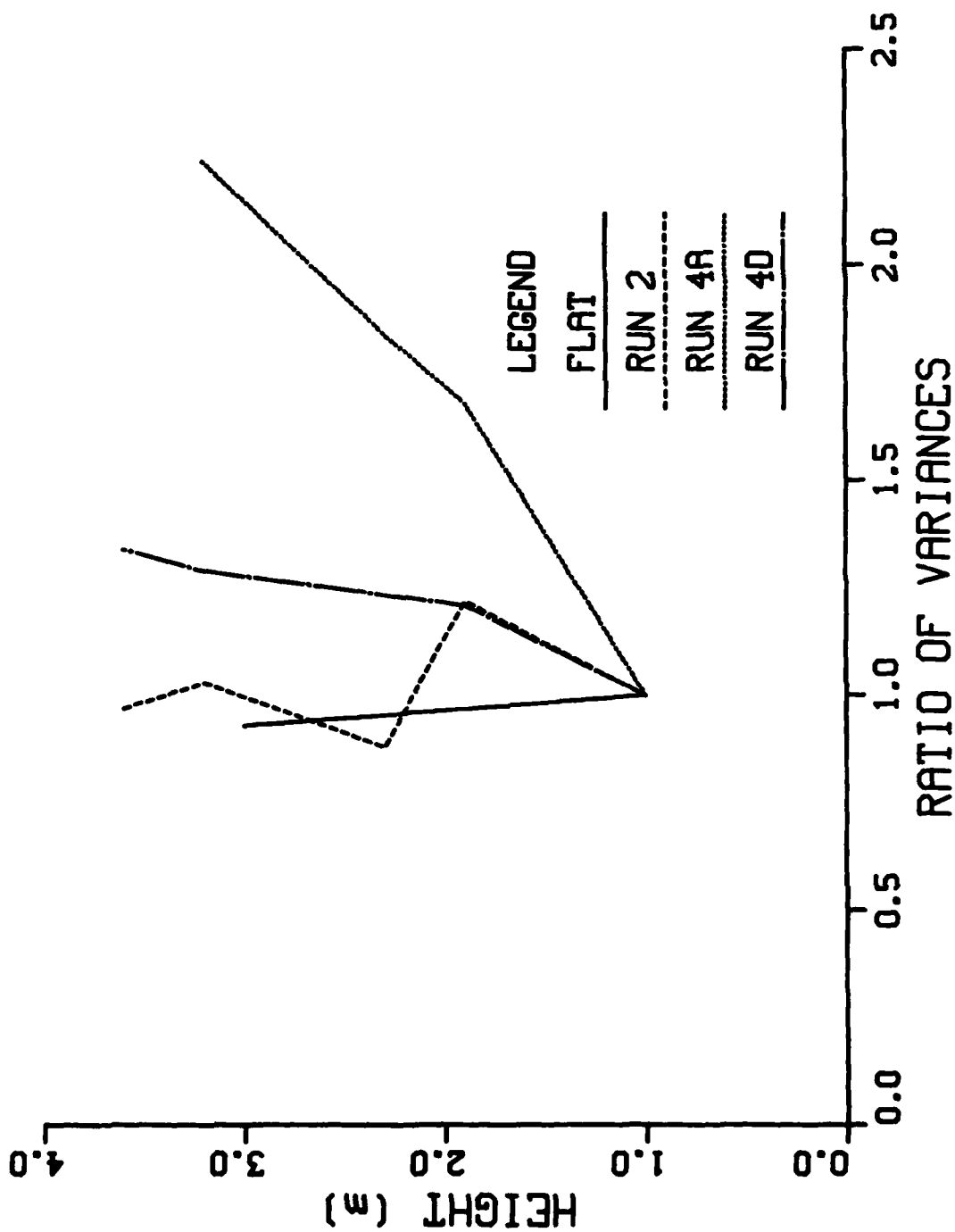


FIGURE 11. Ratios of Variance at Given Height to Variance at 1 m for 4 Cases; Bandwidth 0.01 - 0.1 Hz

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